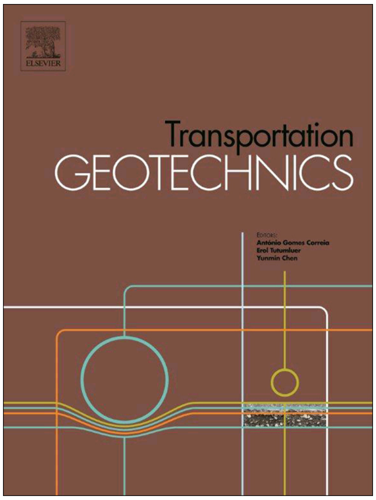

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Asphalt Tenderness in an Australian Runway Overlay

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Key Words

Cyclic shear creep; Asphalt tenderness; Asphalt deformation; Hisingerite; Asphalt mastic.

Abstract

Two runways at a major Australian airport were overlaid with asphalt. Approximately six months after the completion of the works, a number of localised horizontal surface deformations were identified in one runway, concentrated in the heavy braking and turning zone. Initial investigations found no evidence of material non-compliance, systemic construction deficiency or design inadequacy. Both the bond to the underlying asphalt layer and critical aircraft-induced shear stresses were consistent across both runways. The failures were the result of low resistance to cyclic shear creep due to asphalt tenderness.

A different dust source was used in the manufacture of the asphalt surface on each of the two runways. Subsequent investigation also identified a coincidentally concurrent change in the crude oil used in the manufacture of the nominally identical batches of bitumen. Forensic testing of the asphalts' constituent materials found no significant differences except in the petrography of the two dust sources and the post-ageing viscosity of the bitumen when tested two years after construction. The dust used in the manufacture of the poorly performing asphalt contained a potentially detrimental clay mineral called Hisingerite. The change in dust was confounded with the change in measured binder properties. These simultaneous changes in the asphalt mastic constituents were correlated with the reduction in cyclic shear creep resistance observed in the field. Further investigation is required to determine which element of the mastic was responsible for the asphalt tenderness.

1 Introduction

Australian airports are commonly resurfaced every 10-15 years, usually by asphalt overlay. The two runways and associated taxiways at a major Australian airport were resurfaced over a ten month period in 2010 and 2011. The construction operation included the milling of the existing surface with a cold planing machine, cleaning and tack coating with bitumen emulsion. The overlay was generally 50-60 mm thick. Due to an aggregate unavailability part-way through the project, two different fine aggregate (dust) sources were used to manufacture the asphalt. The change in dust source occurred at around the transition from one runway to the other. The two asphalt mixes were otherwise similar.

Approximately six months after the completion of the works, a number of localised horizontal surface deformations were identified in one runway, concentrated in the heavy braking and turning zones. There was no rutting or vertical deformation identified (Figure 1). Some viscous groove closure was evident in the areas where aircraft moved more slowly.

The deformations were triggered by B767 and B737 sized aircraft braking heavily to exit the runway at the first available rapid exit taxiway. Use of this exist taxiway by larger aircraft, such as B777, A380 and B747, is not practical. These larger aircraft roll-through to the end of the runway and brake more gently.

Figure 1. Typical cyclic shear creep failure.

A review of the design and construction quality assurance records found no evidence of inappropriate design, non-conformance with the material specification or systemic construction issue (White 2014a). A second phase of investigation determined that the failures were not a result of debonding or delamination. Rather, the failures were attributed to asphalt tenderness resulting in adequate resistance to repeated near-surface shear stress (White 2014b). This tenderness was only present in one asphalt material.

This investigation aimed to determine if one or more constituent materials within the asphalt could be shown to be responsible for the lack of resistance to Cyclic Shear Creep (CSC) due to tenderness of the asphalt mixture. The mastic, particularly the dust and the binder, were focused on. Background information includes asphalt tenderness and contributing factors. Test results include petrography of the fine aggregate and viscosity of retained bitumen samples. Conclusions address the confounded nature of a measured change in bitumen properties with the change in dust source and the correlation with the CSC failures. The requirement for further work to determine the relative contribution of the fine aggregate and bitumen to the asphalt tenderness is outlined.

2 Background

The asphalt specification and mix design for the asphalt overlay under investigation was typical of that developed for Australian airports over many years (Emery 2005). An acid modified ‘multi-grade’ binder (locally called M1000) was utilised throughout. Although Australia does not Performance Grade bitumen, M1000 typically meets PG 64 E or PG 70 V requirements under AASHTO M332-14. The asphalt mixtures were designed using the Marshall (75 blow per face) method commonly applied to airport asphalt. Non-standard testing included resilient modulus and wheel tracking. The only peculiarity in the specification of the asphalt was the requirement for all coarse and fine aggregate to be basaltic in origin. This requirement is not common in Australia and is based on the airport owner’s belief that other locally available aggregate types have resulted in poor asphalt performance in the past. Key parameters of the two approved mixtures are detailed in Table 1. The overall aggregate particle size distributions are shown in Table 2. While there were differences between the two mixtures, all parameters were within the normal range for well performing airport asphalt in Australia.

Table 1. Comparison of key asphalt characteristics.

Parameter	Asphalt Mix	
Observed CSC resistance	Good	Poor
Fine Aggregate	Dust A	Dust B
Methyl Blue Value for Fine Aggregate (%)	4	8
Multigrade Binder Content (%)	5.8	5.8
Hydrated Lime Content (%)	1.0	1.0
Marshal Stability (kN)	15.3	17.5
Marshal Flow (mm)	3.3	3.1
Air Voids (%)	4.4	4.2
Resilient Modulus (MPa)	3,550	2,790
Indirect Diametrical Tensile Strength (kN)	903	960
Tensile Strength Ratio (%)	99	98
Wheel Tracking (mm)	3.7	3.4

Table 2. Comparison of asphalt particle size distributions.

Australian Standard Sieve (mm)	Percentage Passing by Mass (%)		
	Dust A Asphalt	Dust B Asphalt	Specification Target
19.0	100	100	100
13.2	99	98	100
9.5	84	83	82
6.7	70	71	70
4.75	60	62	60
2.36	63	47	44
1.18	29	31	33
0.600	20	22	25
0.300	13	15	16
0.150	8.8	9.8	10
0.075	6.1	6.5	5

2.1 Asphalt Tenderness

CSC distress is a symptom of asphalt instability or ductility. Asphalt instability can be short or long term (Tarrer & Wagh 1994). Short term instability is often referred to as ‘tenderness’ and usually lasts only a few weeks or months, by which time binder/mastic stiffening hardens the asphalt. Delayed binder stiffening may only be evident in combination with certain aggregate gradations (Crawford 1986). That is, the binder and aggregate grading may combine to result in asphalt tenderness. Long-term asphalt instability is usually attributed to aggregate grading or other characteristic that does not improve over time. However, it may be overcome by natural stiffening of the binder/mastic. Aggregate-related asphalt instability is commonly characterised by rutting of the surface (Sefidmazgi et al. 2012). There was no rutting with the CSC failures at the airport being investigated.

Bognacki et al. (2007) detailed an investigation of horizontal asphalt tenderness. It was concluded that a lack of inter-particle friction and/or aggregate interlock was the cause of shear creep in heavy braking/turning areas at Newark airport. An alternate aggregate source was selected for future works. The specific aggregate characteristic that allowed the deformation was not identified.

Asphalt is a material of very complex mechanical behaviour due to its internal composition and temperature dependence (Zelelew & Papagiannakis 2012). The binder, filler and the fine aggregate combine to form bituminous mastic. The definition of ‘fine’ aggregate varies around the world but, in

Australia it is the material passing the 75 µm sieve. The mastic coats and binds the coarse aggregate particles and provides cohesion to be mix through tensile strength. The mastic is the effective binder within the asphalt mixture (Delaporte et al. 2007) and contributes significantly to asphalt stability and stiffness (Liao et al. 2013). Asphalt behaviour is inherently temperature dependent (Drescher et al. 2010) with stiffness, shear strength and rut resistance all decreasing with increasing temperature.

Excess aggregate retained between the 4.75 mm and 2.36 mm sieves and insufficient or excess material passing the 75 µm sieve may contribute to asphalt tenderness (Tarrer & Wagh, 1994). Soft binder, high temperatures, insufficient asphalt density or moisture in the asphalt may also be factors. The potential contribution of each of the main asphalt constituents to asphalt stability, tenderness and deformation includes:

- **Course aggregate**. Coarse aggregate angularity provides an indication of the internal friction between the aggregate particles that provides rut and deformation resistance (Holleran et al. 2008).
- **Fine aggregate**. Fine aggregate particle shape contributes more to stability and deformation resistance of asphalt than that of the coarse aggregate (Kandhal et al. 1991).
- **Binder**. Tenderness in asphalt can be caused by soft binders (Tarrer & Wagh 1994). Binder is also responsible for high temperature deformation susceptibility and shear creep resistance of asphalt (Scarpas et al. 1997).
- **Filler**. Fillers have different shapes, densities and voids. The percentage of voids in the compacted filler determines the amount of binder that is 'fixed' by the filler. Only the remaining binder is available to effectively coat the coarse aggregate particles and provide asphalt cohesion (Bryant 2005).
- **Mastic**. Some asphalt mixtures, such as those commonly used for Australian airport resurfacing, rely primarily on the properties of the mastic for deformation resistance (Emery 2005).

For the airport under investigation the coarse aggregate and filler were identical for the two asphalt mixtures. These constituents were unlikely to have fundamentally changed during the ten month duration of the project. As a result, this investigation focused on the mastic, specifically the binder and the dust. The dust source was known to have changed part-way through the project. There was no intended change in the binder. However, sources of bitumen being imported into Australia have become more variable and diverse in recent years (Oliver 2009; Neaylon 2013). Changes in imported bitumen source can impact finished binder and asphalt performance (Holleran et al. 2014).

2.2 Binder variability and ageing

Crude oil properties change over time and multiple batches of bitumen manufactured from the same source of crude oil show variability (Abraham 1962). Crude oil variability may require significant changes in the bitumen refining process. The temperatures, pressures, blowing and other processes performed during bitumen manufacture depend on the crude oil source as well as the amount of gas, oil and other petroleum products extracted during the process (Shell Bitumen 2015). These variables impact on the properties of the resulting paving-grade bitumen (Neaylon 2013). As does the original crude oil source (Harnsberger et al. 2011).

There is a widely held perception that bitumen performance has declined over the years (Button & Epps 1985; Oliver 2009; Holleran & Holleran 2010). There have certainly been changes in crude oil sources (Holleran & Holleran 2010; Emery 2005) and associated rheological properties of bitumen (Oliver 2009; Holleran et al. 2014). A lack of confidence in empirical specifications has led to increased use of rheological testing to characterise bitumens (Baumgardner & D'Angelo 2012; Holleran & Holleran 2010). Rheological assessment separates a bitumen sample into Saturate, Aromatic, Resin and Asphaltene groups and measures the proportions of each (Oliver 2009). The assessment is often referred to as SARA analysis. Rheological testing of bitumen is not yet routinely performed in Australia

Bitumen ages over its service life. Its viscosity increases and a hardening of the bitumen occurs through molecular restructuring (Crawford, 1986). This results in a reduced ability to adhere to aggregate and brittle fracture can occur within an asphalt mixture. Bitumen ageing usually triggers asphalt resurfacing as coarse aggregate is lost from the surface. Causes of bitumen ageing are light fraction volatilisation as well as fast (highly reactive hydrocarbons) and slow (benzylic carbon) oxidation (Bianchetto et al. 2007). Oxidation in bitumen generally includes the formation of longer molecules (Wu et al. 2007) and accelerates as temperature increases. Steric hardening (molecular restructuring) occurs over a longer period (Airey 2003). Regardless the viscosity at the time of construction and placement, all asphalt ages and hardens during its service life. Ageing occurs fastest at the pavement surface where exposure to oxygen and atmospheric radiation is greatest. Condition by Rolling Thin Film Oven (RTFO) is routinely used in the laboratory to simulate the ageing of bitumen that occurs during asphalt production (Shell Bitumen 2015). In regard to long-term ageing, the oxidation pressure ageing vessel and the rotating cylinder ageing tests are common (Airey 2003).

2.3 Aggregate Shape and Packing

Aggregates are routinely characterised by a combination of the consensus properties (angularity, size and shape) as well as their source properties (abrasion resistance, strength, deleterious material content and petrography and chemical composition) (Bessa et al. 2012). Aggregate comprises around 95% of an asphalt mixture and its structure plays a significant role in determining the asphalt's mechanical properties (Chen et al. 2005).

Aggregate shape is characterised by form, angularity and texture (Tashman et al. 2007). Coarse aggregate angularity and packing characteristics provide an indication of internal friction between the aggregate particles. Internal friction contributes to mixture deformation resistance (Holleran et al. 2008). More rounded aggregate particles have been shown to result in reduced deformation resistance (Masad & Button 2000). Chen et al. (2005) found that aggregate particle shape affected stability, modulus, tensile strength and rutting of asphalt.

Both coarse and fine aggregates are important for asphalt performance. However, fine aggregate shape contributes more to asphalt deformation resistance than that of the coarse aggregate. The benefit of using angular fine aggregate has been demonstrated by many researchers (Kandhal et al. 1991). An increased proportion of rounded natural sand reduces the shear strength of asphalt mixes (Masad & Button, 2000). Natural (rounded) sand contents are commonly limited to 15% in Australian airport asphalt.

Clay minerals are commonly present in quarried aggregate sources (Little & Epps 2001). Clay minerals vary widely and their chemical composition and morphology can have significant impact on a fine aggregate's engineering performance. Although clay minerals can also affect coarse aggregates, the comparatively small surface area of coarse aggregate results in most of the clay minerals being trapped inside the aggregate particles. It follows that clay mineral properties are more important for fine aggregate sources, where they are incorporated in the mastic and can be exposed to air and moisture as well as interacting with the asphalt binder.

X-Ray Diffraction (XRD) is a semi-quantitative analysis of the chemical composition of powdered (30 µm and below) rock samples. It is routinely used for mineral composition analysis of aggregate sources. Following calibration of equipment and analysis software, XRD is very accurate and assesses the whole of the powdered sample (Amaral et al. 2006). Other methods only assess the composition of the exposed particle surfaces. XRD allows visually identifiable particles of interest within a crushed aggregate sample to be separated and powdered in order to assess their contribution to the fine aggregate chemical composition. Separation of the actual fine aggregate particles would be impractical.

3 Investigation Methods

The various constituents of the two asphalt mixtures were assessed by various methods outside of the project specification. Fourteen retained binder samples were recovered from storage and tested to screen for uniformity across the project. Bitumen rheology was assessed as an indicator of crude oil variability. Post-RTFO viscosity was measured on the (then) two year old samples as the primary material compliance criterion. Retained binder was also used to manufacture mastic (binder, filler and fine aggregate) for Dynamic Shear Rheometer (DSR) testing.

Representative samples of the common active filler were assessed against non-specification tests. Samples of the fine aggregates (dusts) were also tested for non-specification properties including chemical composition by XRD. Following the XRD analysis, further geological testing was performed on the fine aggregate components of interest to allow identification of the specific minerals.

The common course aggregate source was not assessed. The production compliance records were reviewed and no evidence of any change or variability in the coarse aggregate was identified. The quarry was inspected and no significant change in the quality of rock in the working face was observed.

Table 3 summarises the assessment of each asphalt material constituent. Australian Standard (AS) tests were adopted where available. Where not available, recognised international test methods were preferred over proprietary test protocols.

Table 3. Constituent testing plan.

Constituent	Assessment	Test Method(s)	Basis
Binder	Compositional Analysis	SARA by Iatroscan (proprietary thin-layer chromatography-flame ionisation detection system)	Assessment of the relative wax, asphaltene and other fractions
Binder	Post RTFO Viscosity	AS 2341.10 AS 2341.2	Difference in response to aging and consistence across the airfield
Binder	Pre and post RTFO temperature-frequency sweeps	AS 2341.10 Proprietary Dynamic Shear Rheometer protocol	Difference in response to aging and consistence across the airfield
Active Filler	Voids in Compacted Filler	AS 1141.17	The potential for binder to become 'fixed' within porous fillers and not available to contribute to the asphalt's stability.
Fine Aggregate	Angularity and Packing	ASTM 1252-06	The significant contribution of fine aggregate shape and friction to contribute to asphalt stiffness and resistance to deformation
Fine Aggregate	Petrography	Chemical composition analysis by proprietary X-Ray Diffraction	The potential for a geological difference in the two dusts given the dust was the only constituent of different sources in the two mixes
Mastic	Pre and post RTFO temperature-frequency sweeps	AS 2341.10 Proprietary Dynamic Shear Rheometer protocol	The potential for some interaction between the fine aggregate, filler and binder

4 Results and Analysis

4.1 Constituent Testing Results

With the exception of the petrographic analysis of the two dust sources and the binder uniformity testing, there was no significant difference found between the constituent materials utilised in the manufacture of the two asphalt mixtures (Table 4). The binder testing and petrography results are discussed below.

Table 4. Constituent testing results.

Constituent	Test(s)	Result
Binder	Compositional Analysis	Variable across all samples with Asphaltene contents of 28-37% but not indicative or correlated with field performance
Binder	Post RTFO Viscosity	Significant differences discussed in detail below (section 4.2)
Binder	Dynamic Shear Rheometer	η* at 60℃ and 1 rad/s consistently between 1200 and 1700 Pa.s
Fine Aggregate	Angularity and Packing	Ranged from 42 to 46% for the three dust sources
Dust Source	Petrography	Significant differences discussed in detail below (section 4.3)
Mastic	Dynamic Shear Rheometer	η* at 60℃ and 1 rad/s consistently between 5,000 and 6,000 Pa.s

4.2 Binder Testing

The post-RTFO viscosity was measured at 60℃ for the fourteen retained binder samples. Eight samples represented M1000 batches used to manufacture Dust A asphalt. Six samples were from M1000 batches used to manufacture Dust B asphalt. Appendix A contains the binder testing results. Table 5 summarises the calculated mean and standard deviations. The results of the compliance testing (at the time of manufacture) are also summarised. The time of manufacture test results were all compliant with specification. Two-sided T-tests for equality of means were performed assuming non-equal population size and variance. Based on the screening testing, the probability of the two sub-populations of bitumen coming from the same overall population was calculated to be 0.2%. At the time of manufacture this probability was 4.6%.

Table 5. Binder post-RTFO test results

Binder Sub-Population	Time of Manufacture Testing (2011)		Screening Testing (2013)	
	Mean	Standard Deviation	Mean	Standard Deviation
Dust A Asphalt	4,776	688	5,248	630
Dust B Asphalt	5,657	781	6,698	756
T-test on means p-values	0.046		0.002	

The binder testing indicated some difference in the binder used in the manufacture of Dust A and Dust B asphalts. The difference was magnified by retained sample storage time. The binder used in Dust B asphalt production had a higher viscosity that the Dust A asphalt binder. Higher viscosity would generally be associated with improved resistance to shear and deformation. However, various researchers have shown that bitumen viscosity is not a reliable indicator or bitumen shear creep resistance (D'Angelo et al. 2007). The increase in post-RTFO viscosity was an indicator of a significant difference between the batches of binder used in the manufacture of the two asphalts. It was not, however, a specific explanation for the observed asphalt tenderness.

The bitumen supplier was advised of the observed CSC failures and the bitumen test results (Table 5). The supplier subsequently advised that the specific crude oil blend had changed in April 2011. The change appeared to be minor (Table 6) and coincidentally occurred at the same time as the change in dust source. The change in the crude oil blend may have also indicated a change in oil refining and M1000 manufacturing processes.

Table 6. Pre and Post April 2011 crude oil blends

Period	Crude Oil Source as a Percentage of Feedstock	
	Arab Light	Basrah Light
Pre April 2011 (Feedstock A)	92%	8%
Post April 2011 (Feedstock B)	97%	3%

4.3 Petrographic and Geological Assessment

Initial XRD assessment of the two dust sources determined that both contained comparable amounts of clay minerals within an otherwise typical olivine basalt. Further analysis of observed brown chips within Dust B determined that what the initial XRD assessment reported as Smectite clay was in fact a rare clay mineral called Hisingerite. Negligible Hisingerite existed in Dust A (Table 7).

Table 7. Fine aggregate source Hisingerite content

Dust Source	Dust A	Dust B
Percentage of Clay Minerals in Dust	8%	13%
Percentage of Clay that was Hisingerite	<1%	82%
Percentage of Hisingerite in Dust	Negligible	10.7%

Hisingerite is a rarely encountered and poorly studied clay mineral. First described in 1810, Hisingerite has been variously regarded as a non-crystalline silicate, a ferric allophane, a poorly crystallised nontronite and an iron rich spherical halloysite (Brigatti et al. 2013). Hisingerite is characterised by the presence of spherical bodies which are curved and largely in a random arrangement. These spherical bodies are very different from the flat sheets observed in saponite, nontronite and other more common clays (Eggleton & Tilley1998).

Hisingerite was previously identified in a basalt quarry within the same region as the basalt quarry from which Dust B was sourced (Shayan 1984). The previously identified local Hisingerite had a high pH and very low cation exchange capacity, indicative of negatively charged particle surfaces. This was confirmed by the absorption of 3.4 grams of methylene blue dye by 1 g of Hisingerite in a 4% aqueous suspension.

The locally identified Hisingerite is highly hydrous, even more so than many other identified Hisingerite sources around the world (Shayan 1984).

No literature could be found on the physical effects of Hisingerite on the performance of civil construction materials such as asphalt, concrete or crushed rock. Specialist geotechnical interpretation of the unique properties of Hisingerite minerals indicated potential interaction with acid modified binder (such as M1000) and lime (used in both mixtures) in the production and performance of asphalt. The highly hydrous nature of Hisingerite could trap excess moisture in the asphalt mastic. These potential interactions may adversely affect mastic stability and could cause tenderness in the asphalt surface.

4.4 Binder or Dust?

At the time of construction there was an intended change in the fine aggregate (dust source) at the transition from one runway to the other. The bitumen testing and subsequent review of feedstock composition identified a previously unknown change in the crude oil blend used to manufacture the binder. This change occurred at around the same time as the change in dust source. Although the change in feedstock appeared minor, the impact on post-RTFO viscosity after two years of retained sample storage was significant. Rather than two asphalts containing only a different dust source, the difference in the two asphalts extended to bitumen properties resulting from the change in crude oil blend. These changes in binder and dust were concurrent and correlated with the location of CSC failures (Figure 2).

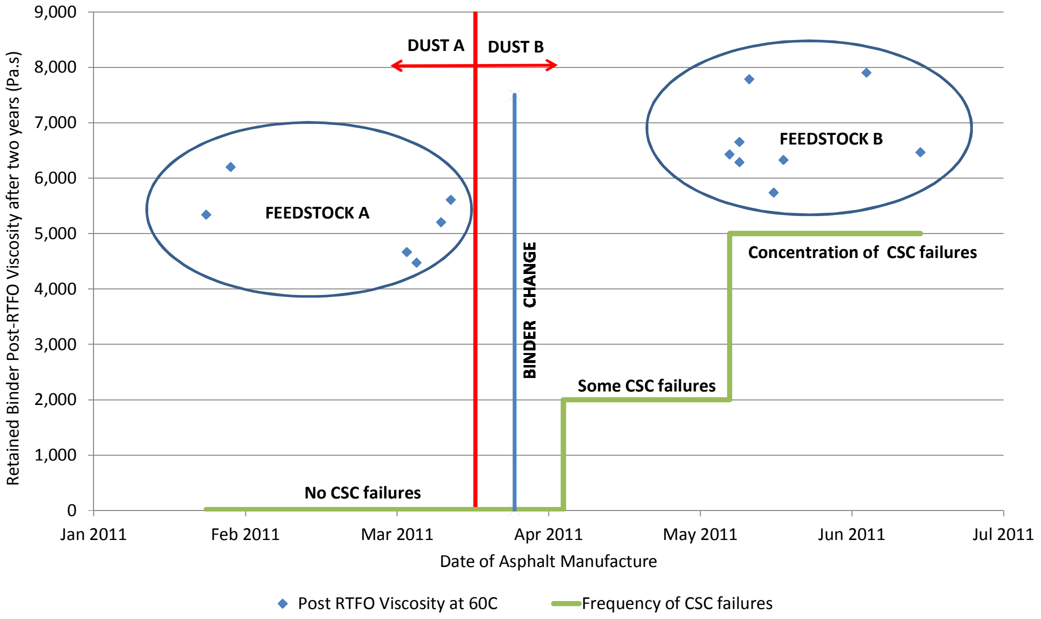

Figure 2. Time series of dust and binder changes with asphalt performance.

The dust change and the binder feedstock change were confounded and their relative impact on the field performance of the asphalt surface could not be separated. Further investigation is required to determine which element of the mastic was responsible for the observed asphalt tenderness.

5 Performance Monitoring

The performance of the asphalt overlay was monitored since the first CSC failures were identified in 2012. Inspections were performed on a periodic basis and were logged from June 2013. The location, number and severity of the various failures were tracked. The number of newly identified CSC failures is shown in Figure 3. At no stage were CSC failures identified in Dust A asphalt.

By May 2014 the performance of Dust B asphalt significantly improved. This improvement in performance resulted from natural binder ageing overcoming the original lack of CSC resistance. The operationally-necessary replacement of the most CSC susceptible areas may have also assisted. As the binder continues to harden over time, it is likely that the performance of the asphalt surface will continue to improve. At the time of writing (March 2015) no additional CSC failures had been observed in either the Dust A or Dust B asphalt.

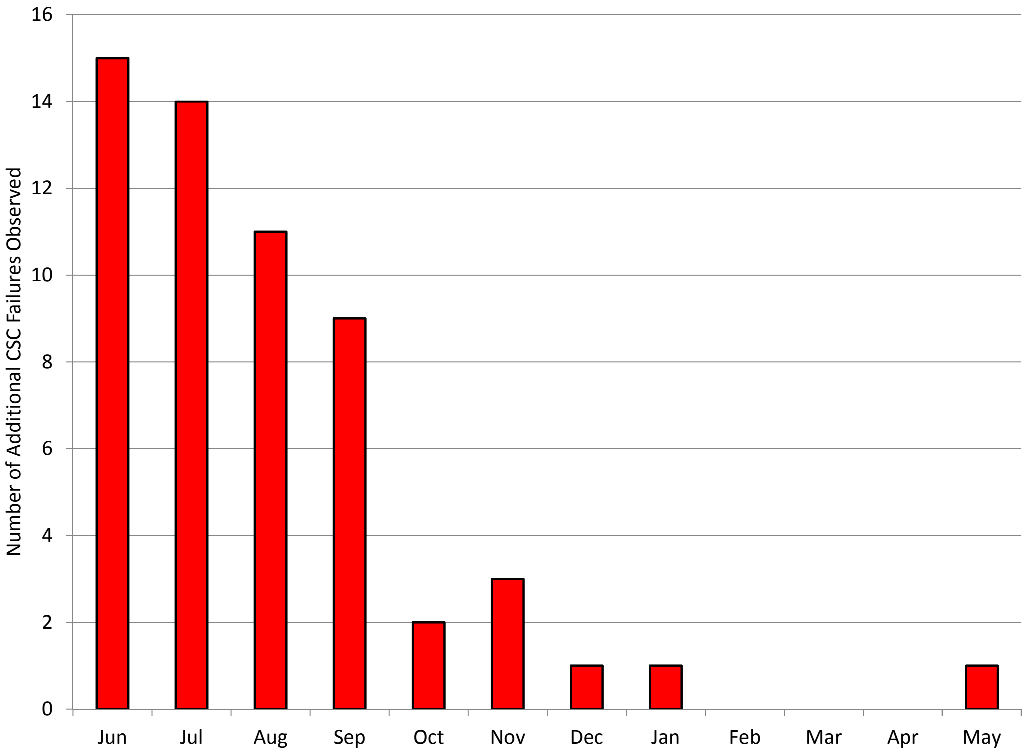

Figure 3. New CSC deformations June 2013 to May 2014.

6 Conclusions

The slippage-type failures observed in one runway at the airport resulted from a lack of CSC resistance in one asphalt mixture but not the other. The difference in the CSC resistance of the two mixtures was likely the result of the intended change in the dust source or the unintended change in bitumen properties. Some interaction and combination of the two changes may also have occurred. The change in mastic constituents was significant to asphalt surface performance only when exposed to high shear stresses resulting from the heavy braking of aircraft.

Due to the confounded nature of the binder and dust changes, the relative (or combined) contribution of each could not be separated with the information available. Further investigation is required to determine whether the presence of Hisingerite in the Dust B clay minerals was detrimental to asphalt performance and tenderness. Similarly, further investigation is required to determine the significance of the crude oil source change on the performance of the binder. A fully factorial performance-based assessment of mastics manufactured from each dust in combination with each binder is necessary.

Regardless the root cause of the tenderness of the asphalt investigated, an undetected change in bitumen feedstock resulted in a significant difference in critical bitumen properties. This highlights the need for Australia to move towards performance-based specifications for binders in high stress applications, including asphalt for runway surfacing.

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Vitae

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Appendix A
Bitumen Post-RTFO Viscosity at 60°C

Sampling Date	Feedstock	Time of manufacture (2011)	Screening testing (2013)
28 Jan 2011	A	4,740	5,338
02 Feb 2011	A	5,860	6,199
10 Mar 2011	A	4,077	4,664
12 Mar 2011	A	4,673	4,472
17 Mar 2011	A	4,076	5,204
19 Mar 2011	A	5,228	5,608
15 May 2011	B	5,673	6,428
17 May 2011	B	4,875	6,284
17 May 2011	B	6,311	6,653
19 May 2011	B	5,182	7,786
24 May 2011	B	4,328	5,738
26 May 2011	B	6,221	6,327
21 Jun 2011	B	6,274	7,903
23 Jun 2011	B	6,388	6,465